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Intraoperative Measurement of Pericardial Constraint: Role in Ventricular Diastolic Mechanics

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The pressure of pericardial constraint was measured in 20 patients undergoing elective cardiac surgery (10 in Group I with normal cardiac size; 10 in Group II with cardiomegaly) using a catheter with a collapsible latex end balloon. Right atrial pressure and other hemodynamic variables including right ventricular stroke work index were also measured before and after the pericardium was widely opened. The pericardium was grossly normal in all patients and only small physiologic effusions were present.

In Group I mean pericardial pressure was 8 ± 2 mm Hg as was mean right atrial pressure. In Group II mean pericardial pressure was 6 ± 2 mm Hg versus mean right atrial pressure of 10 ± 5 mm Hg ($p < 0.05$). Excluding 2 of the 20 patients with outlying data, pericardial pressure showed linear correlation with right atrial pressure ($r = 0.689$). In Group I right ventricular stroke work index rose from 5.0 ± 2.0 to 6.4 ± 2.1 g-m/m^2 ($p < 0.01$) after pericardiotomy with no significant increase in mean right atrial pressure; similar findings in Group II were consistent with removal of external constraint.

Thus, even in the absence of an abnormal effusion the normal pericardium exerts a significant pressure on the heart, which is often similar in magnitude to right atrial pressure. In certain notable exceptions, however, right atrial pressure far exceeds pericardial pressure. Such pericardial constraint has important implications for ventricular diastolic mechanics.

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Because of its high collagen content the parietal pericardium is almost not distensible once a certain intrapericardial volume is attained (1). There has been a recent resurgence of interest in the hypothesis that the normal pericardium provides a constraining influence on the heart during diastole (2–6). A simple requirement for the constraining effect is that the parietal pericardium exert a significant force or pressure on the external cardiac surface. Results of directly measured pericardial pressure in the absence of an abnormal pericardial effusion have been conflicting, however, open catheters yielding much lower values than balloon-tipped devices (1,7,8). Using a balloon catheter, Refsum et al. (9) found the pressure of pericardial constraint in open chest dogs essentially equal to right ventricular mid-diastolic pressure over a wide range of volume states, reminiscent of the findings of Holt et al. (1). While the proper method of pericardial pressure measurement in the absence of free pericardial effusion remains controversial (10), an indirect validation for the balloon catheter method was recently offered (11) because the balloon measurement equals the decrease in left ventricular diastolic pressure after pericardiotomy at a given diastolic diameter.

Despite mounting experimental evidence (2–5) and inferential observations in certain acute cardiac disorders (12–14), the general clinical importance of pericardial constraint remains unclear. If pericardial constraint equals right ventricular diastolic pressure over the range of right heart volumes occurring with respiratory maneuvers, then the more easily measured right ventricular diastolic pressure should behave as an external limiting pressure, analogous to that present in cardiac tamponade. Thus, transient underfilling

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of the left ventricle during normal or forced inspiration conceivably may reduce left ventricular diastolic pressure sufficiently to equalize with this limiting pressure, manifesting as an inspiratory form of diastolic equalization (15). Such "inspiratory tracking" of left and right ventricular diastolic pressures has been cited in certain heart failure states (16) and conditions of near-normal ventricular function (15) as indirect evidence that pericardial constraint generally may equal right ventricular diastolic pressure in humans. The current report details efforts to test this hypothesis by direct measurement of the pressure of pericardial constraint in patients undergoing cardiac surgery.

Methods

Study patients. Twenty patients undergoing elective cardiac surgery for the first time were enlisted. Each subject gave written informed consent for the protocol, which was approved by the institutional human use committee. According to the original design of this project, two separate patient groups were studied: Group I, 10 patients with a cardiothoracic ratio on chest radiograph of 0.5 or less and Group II, 10 patients with a cardiothoracic ratio greater than 0.5.

The 10 patients in Group I included 9 patients with coronary artery disease (triple vessel in 7, double vessel in 2) and 1 patient with aortic stenosis. Five of the 10 patients had clinical evidence of previous myocardial infarction, 3 in the inferior and 2 in the anterior distribution. All Group I patients were men with normal sinus rhythm; the mean age was 58 ± 9 years. The cardiothoracic ratio was 0.47 ± 0.03 (± SD) and the angiographic left ventricular ejection fraction was 0.60 ± 0.14.

All 10 patients in Group II had chronic valvular heart disease: 3 with aortic stenosis and regurgitation, 3 with mitral stenosis and regurgitation (including 1 with associated aortic insufficiency), 1 with aortic insufficiency and mitral stenosis and 1 each with aortic insufficiency, aortic stenosis or mitral regurgitation. Three patients also had coronary artery disease (single vessel in two and triple vessel in one), including two with clinical evidence of previous myocardial infarction (aortic stenosis with anterior infarct, aortic stenosis and insufficiency with inferior infarct). All 10 Group II patients were men; 3 (all with mitral stenosis) had atrial fibrillation and the remaining 7 had sinus rhythm; the mean age was 58 ± 13 years. The cardiothoracic ratio was 0.59 ± 0.06 ($p < 0.001$ versus Group I) and the left ventricular ejection fraction was 0.42 ± 0.16 ($p < 0.05$ versus Group I).

The patients with coronary artery disease received their antianginal medications up to the time of surgery. All patients received intravenous fentanyl for initial anesthesia. Seven patients in Group I and four patients in Group II received supplemental inhalational anesthesia: Isoflurane (five patients in Group I, one patient in Group II), enflurane (one patient in Group I, two patients in Group II) or halothane (one patient in each group). One patient in Group II received intravenous diazepam in addition to fentanyl. Intravenous fluids and vasoactive medications were administered according to the independent judgment of the anesthesiologist. By the time of pericardial pressure measurement (see later), Group I patients had received 1,600 ± 640 ml and Group II 930 ± 600 ml intravenous fluids ($p < 0.05$ versus Group I). At this time eight patients in Group I and seven in Group II were receiving intraveous nitroglycerin or sodium nitroprusside, or both.

Hemodynamic variables. Radial artery pressure was measured by direct cannulation. Pulmonary artery, pulmonary wedge and right atrial pressures were measured along with duplicate thermodilution cardiac outputs using a balloon-directed triple lumen catheter. Cardiac pressures were measured with a 72 inch (183 cm) connecting tubing using three fluid-filled strain gauges with zero level at midchest height and were recorded simultaneously with the electrocardiogram. Average pressure measurements were obtained during the expiratory phase of positive pressure ventilation. Systolic and diastolic radial and pulmonary artery pressures were averaged over approximately eight cardiac cycles and mean values calculated as (systolic + 2 × diastolic)/3. Pulmonary wedge, right atrial and pericardial pressure tracings were digitized by hand at 0.2 second intervals and averaged over several cardiac cycles (total of 20 to 30 data points). This method was used in the presence of sinus rhythm or atrial fibrillation. The pericardial pressure reported in Table 1 was measured over the right atrium; measurements at other positions are reported later. Mean transmural right atrial pressure was calculated as right atrial minus pericardial pressure with the pericardium closed or as right atrial pressure with the pericardium open (assuming a pericardial pressure of zero in this condition). Assuming that the septal area is one-third of the total external surface of the left ventricle (17,18), the mean transmural left ventricular filling pressure was calculated as (pulmonary wedge − ⅓ right atrial − ⅔ pericardial pressure) with the pericardium closed or as (pulmonary wedge − ⅓ right atrial pressure) with the pericardium open.

Cardiac index, left and right ventricular stroke work indexes and systemic and pulmonary vascular resistances were calculated in the standard manner (19). In the presence of aortic or mitral stenosis left ventricular stroke work index was calculated using mean arterial or left ventricular filling pressure, approximately corrected according to: transvalvular gradient ≃ transvalvular gradient$_C$ × (cardiac output/cardiac output$_C$)^2, where the subscript C denotes measurements in the catheterization laboratory (20). In the presence of aortic or mitral regurgitation, or both, left ventricular stroke work index was calculated with a total left ventricular output ≃ cardiac output/(1 − regurgitant frac-

Table 1. Pericardial Pressure and Hemodynamic Measurements in 20 Patients

	Group I (n = 10)			Group II (n = 10)		
	Pericardium Closed	Pericardium Open	p Value*	Pericardium Closed	Pericardium Open	p Value*
Mean pericardial pressure (mm Hg)	8 ± 2	—	—	6 ± 2	—	—
Mean right atrial pressure (mm Hg)	8 ± 2	7 ± 2	NS	10 ± 5†	9 ± 5	NS
Mean transmural right atrial pressure (mm Hg)	0 ± 2	7 ± 2	<0.001	4 ± 5	9 ± 5	<0.001
Mean pulmonary wedge pressure (mm Hg)	11 ± 3	13 ± 3	<0.05	24 ± 10	26 ± 9	0.06
Mean transmural left ventricular filling pressure (mm Hg)	4 ± 3	11 ± 3	<0.001	13 ± 8	18 ± 10	0.06
Mean pulmonary artery pressure (mm Hg)	16 ± 3	18 ± 3	<0.05	33 ± 12	34 ± 11	NS
Mean arterial presure (mm Hg)	82 ± 12	90 ± 9	0.06	79 ± 15	81 ± 14	NS
Heart rate (beats/min)	64 ± 16	65 ± 16	NS	91 ± 26	90 ± 29	NS
Cardiac index (liters/min per m^2)	2.3 ± 0.3	2.5 ± 0.4	NS	2.0 ± 0.6	2.1 ± 0.7	NS
Left ventricular stroke work index (g-m/m^2)	40 ± 10	46 ± 9	0.06	50.5 ± 35.2	56.3 ± 37.0	NS
Right ventricular stroke work index (g-m/m^2)	5.0 ± 2.0	6.4 ± 2.1	<0.01	6.2 ± 2.9	7.6 ± 3.7	<0.05
Systemic vascular resistance (dynes-s-cm^{-5})	1,300 ± 270	1,400 ± 280	NS	1,500 ± 580	1,400 ± 420	NS
Pulmonary vascular resistance (dynes-s-cm^{-5})	96 ± 20	87 ± 32	NS	240 ± 140	160 ± 90	<0.05

*Pericardium open versus closed; †$p < 0.05$ versus mean pericardial pressure.

tion), where the regurgitant fraction was measured in the catheterization laboratory as the difference between angiographic and thermodilution measurements of left ventricular output.

Pericardial constraint pressure measurement. Pericardial pressure was measured with a thin-walled latex balloon attached at the tip, and about 5 cm proximal, of a 7F six side-holed Cook UCLA Straight Special catheter (21) (that is, so that the portion of the catheter with the pressure measurement holes was within the balloon). The physical problem of pressure between two closely apposed surfaces was simulated by placing the balloon catheter in a metal cannister, between the cannister bottom and a form-fitting plastic bag filled with water. Assuming no transmural gradient across the wall of the plastic bag, the intersurface pressure was measured simply as the hydrostatic pressure within the water with a zero reference at the bottom of the cannister. For each balloon catheter a particular saline filling volume was found that reproducibly allowed intersurface pressure measurement to be accurate within 1 mm over a 2 to 20 mm Hg range varied by siphoning the cannister water. This accuracy was maintained over temperatures ranging from 20 to 37°C and was verified before and after use of each balloon catheter (single use per catheter). McMahon et al. (22) used a partially inflated 7 liter latex weather balloon pressed against a flat surface to produce intersurface pressure that was measurable inside the balloon and varied by placing weights on top of the balloon. Our method is analogous to that of McMahon et al., but has the advantage of easily controlled quasistatic variation of intersurface pressure (by siphoning the cannister water), and can be performed with a readily available office refuse can.

The balloon measurement filling volume was 2.3 ± 0.6 ml. When properly seated and filled, a representative balloon covered about 7 to 8 cm^2 of surface between two approximated layers, with an average thickness of 2 to 3 mm between the layers. The frequency response of the saline-filled balloon catheter was tested in an electromagnetically driven water-filled chamber with a micromanometer reference (Multifunction Pressure Generator model MPG-30, Millar Instruments, Inc.). The balloon catheter-micromanometer pressure/amplitude ratio was within 5% of unity at frequencies below and including 20 Hz.

After median sternotomy the pericardium was cannulated with the balloon catheter in the fluid-filled but collapsed state using a 3 mm midline incision at the level of the atrioventricular junction. The balloon catheter was positioned over the right atrium, secured with a pericardial purse-string suture around the entrance wound, filled beyond its stressed volume and then reemptied to seat between the visceral and parietal layers, and finally filled with its predetermined measurement filling volume. In 11 patients (5 in Group I, 6 in Group II) balloon pericardial pressure was also measured over the right ventricular outflow area and over the left ventricular lateral wall. In 16 patients (7 in Group I, 9 in Group II), after the balloon catheter was removed pericardial pressure was measured for comparison over the right atrium with an open-ended Cook UCLA Straight Special (that is, identical catheter shaft, but without the balloon). During subsequent data analysis the pericardial pressure tracings at each position were averaged by hand at 0.2 second intervals over 20 to 30 data points. However, the systolic wave sometimes detected over the left ventricle was excluded from the pericardial pressure average.

Protocol. The radial and pulmonary artery catheters were inserted preoperatively in the surgical suite. In 15 patients (8 in Group I, 7 in Group II) right atrial pressure was measured during general anesthesia, just before sternotomy.

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After median sternotomy the pericardial space was cannulated as detailed earlier, and hemodynamic variables were measured. The pericardium was then widely opened from base to apex, and hemodynamic variables were remeasured with several sutures holding the pericardium away from the heart to form a pericardial cradle. A small pericardial sample was then incised for histologic examination (hematoxylin-eosin stain, light microscopy) and the rest of the cardiac operation was performed in the usual fashion.

Data analysis. All data are provided as mean ± standard deviation. Hemodynamic measurements before and after opening the pericardium were compared using the paired Student's *t* test. Clinical variables in Groups I and II were compared using the unpaired Student's *t* test. The pericardial pressure measurements at three separate locations were compared using one-way analysis of variance. The null hypothesis was rejected at the 0.05 level. The correlation between mean pericardial pressure (measured over the right atrium) and mean right atrial pressure was tested using least squares linear regression analysis (BMDP P1R) (23).

Results

Pericardial constraint measurement. The balloon pericardial pressure measurement was performed in all patients studied, and aside from occasional ectopic beats there were no significant ill effects. In one patient the right atrium was inadvertently perforated with the subsequent straight pericardial catheter; this was easily repaired without sequelae. Table 1 shows results of pericardial pressure measurement over the right atrium with related hemodynamic data. In Group I, both mean pericardial pressure and mean right atrial pressure were 8 ± 2 mm Hg. In Group II, mean pericardial pressure was 6 ± 2 mm Hg, while mean right atrial pressure was 10 ± 5 mm Hg ($p < 0.05$). In five patients in Group I and six in Group II pericardial pressure was 7 ± 2 mm Hg measured over the right ventricular outflow tract, 8 ± 3 mm Hg over the left ventricle, and 7 ± 2 mm Hg over the right atrium (p = NS). In seven patients in Group I and eight in Group II, pericardial pressure measured by open catheter was 6 ± 3 mm Hg versus the balloon measurement of 7 ± 2 mm Hg (p = NS).

Effects of pericardiotomy on hemodynamic variables (Table 1, Fig. 1). In eight patients in Group I and seven in Group II, right atrial pressure was 10 ± 4 mm Hg when measured just before sternotomy and again after sternotomy at the time of pericardial pressure measurement. After pericardiotomy in Group I there were significant increases in mean transmural right atrial pressure (0 ± 2 to 7 ± 2 mm Hg, $p < 0.001$), mean pulmonary wedge pressure (11 ± 3 to 13 ± 3 mm Hg, $p < 0.05$), mean transmural left ventricular filling pressure (4 ± 3 to 11 ± 3 mm Hg, $p < 0.001$), mean pulmonary artery pressure (16 ± 3 to 18 ± 3 mm Hg, $p < 0.05$) and right ventricular stroke work index

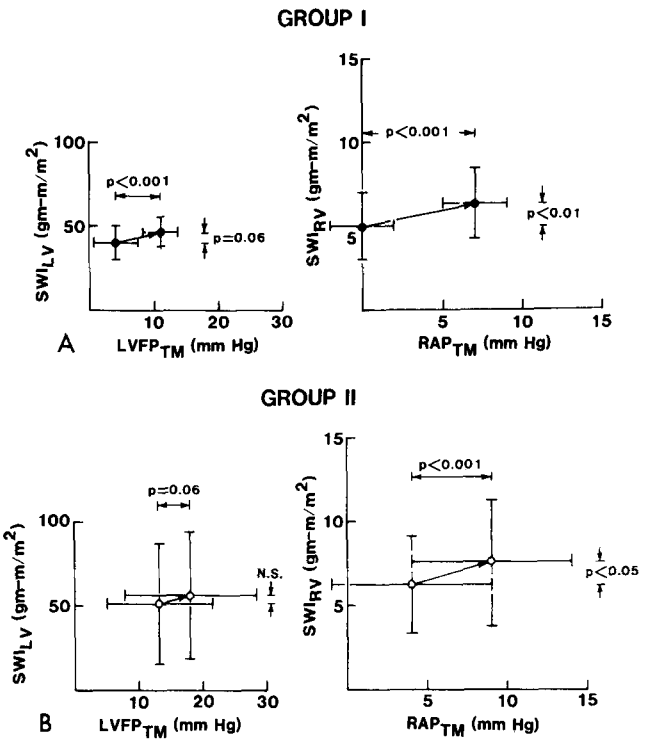

Figure 1. Plots of left (LV) and right ventricular (RV) stroke work index (SWI) versus transmural left ventricular filling pressure ($LVFP_{TM}$) or right atrial pressure (RAP_{TM}), respectively, in Group I (**A**) and Group II (**B**). The **bars** give standard deviation and the **arrows** connect pre- to postpericardiotomy measurements.

(5.0 ± 2.0 to 6.4 ± 2.1 g-m/m^2, $p < 0.01$). After pericardiotomy in Group I there were borderline significant increases in mean arterial pressure (82 ± 12 to 90 ± 9 mm Hg, p = 0.06) and left ventricular stroke work index (40 ± 10 to 46 ± 9 g-m/m^2, p = 0.06). In Group I there were no significant changes in mean right atrial pressure, heart rate, cardiac index or vascular resistances after opening the pericardium.

In Group II, pericardiotomy caused a significant increase in mean transmural right atrial pressure (4 ± 5 to 9 ± 5 mm Hg, $p < 0.001$) and right ventricular stroke work index (6.2 ± 2.9 to 7.6 ± 3.7 g-m/m^2, $p < 0.05$) as well as a significant decrease in pulmonary vascular resistance (240 ± 140 to 160 ± 90 dynes-s/cm^{-5}, $p < 0.05$). There were borderline significant increases in mean pulmonary wedge pressure (24 ± 10 to 26 ± 9 mm Hg, p = 0.06) and mean transmural left ventricular filling pressure (13 ± 8 to 18 ± 10 mm Hg, p = 0.06). In Group II opening the pericardium caused no significant change in mean right atrial pressure, mean pulmonary artery pressure, mean arterial pressure, heart rate, cardiac index, left ventricular stroke work index or systemic vascular resistance. Figure 1 shows plots of right ventricular stroke work index versus mean transmural right atrial pressure, and left ventricular stroke work index versus transmural left ventricular filling pressure, respectively, before and after pericardiotomy in Groups I and II.

Linear regression analysis. Figure 2 shows the plot of mean pericardial pressure versus mean right atrial pressure in the 20 patients studied. Excluding the two outliers the linear regression was: pericardial pressure = 0.69 × right atrial pressure + 1.68, with standard regression coefficient 0.689, and standard error of estimation = 1.59 mm Hg ($p < 0.01$). The data of eight patients fell on the identity line, and superimposed tracings of pericardial and right atrial pressure in such patients showed nearly exact phasic tracking in diastole (Fig. 3), albeit sometimes with fine oscillation in the pericardial pressure waveform.

Separate analysis of patients in Group I gave the relation: pericardial pressure = 0.49 × right atrial pressure + 3.90, with standard regression coefficient = 0.586 and standard error of estimation = 1.42 mm Hg ($p = 0.075$). Separate analysis of all patients in Group II showed no significant correlation. However, analysis of Group II excluding the two outliers gave the relation pericardial pressure = 0.78 × right atrial pressure + 0.08, with standard regression coefficient 0.851, and standard error of estimation 1.28 ($p < 0.01$).

Pericardial tissue. The pericardium appeared grossly normal in all patients studied and only small physiologic effusions were apparent after pericardiotomy. In Group I, eight technically satisfactory pericardial biopsy specimens showed normal fibrocollagenous histologic features, but with local hemorrhage (presumably due to surgical trauma) in one and perivascular infiltration by segmented neutrophils (of unknown significance) in two; six perpendicularly cut sections showed a mean collagen thickness of 0.8 ± 0.2 mm. In Group II, 10 pericardial biopsy specimens showed normal fibrocollagenous tissue except for local hemorrhage in 5; 8 perpendicularly cut sections showed a mean collagen thickness of 0.7 ± 0.2 mm (not significantly different from Group I).

Figure 2. Plots of mean pericardial pressure (PP) versus mean right atrial pressure (RAP) in the 20 patients studied. Eight points fell on the identity line and overall there was a significant linear regression relation (excluding the two outliers from Group II).

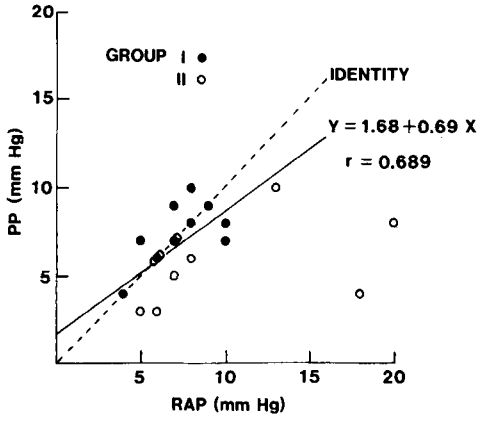

Figure 3. Representative superimposed pericardial (PP) and right atrial (RAP) pressure tracings, both from two Group I patients. Note the close phasic relation during diastole. ECG = electrocardiogram.

Discussion

Intersurface pressure measurement. While a simple open-ended catheter may be inserted into the normal pericardial space without distorting the original anatomy, this method may seriously underestimate the true level of constraint in the absence of a sufficient effusion. Consider, for instance, a hypothetical canine experiment in which aggressive volume expansion results in a high pericardial constraint pressure. If an open-ended pericardial catheter were then vigorously aspirated, a potentially negative pressure measurement would result, having little relation to the true pressure exerted by the pericardium on the epicardial surface. A catheter with a flat end balloon just filled to its equilibrium volume (the volume that exists at zero transmural pressure) has been proposed as a superior means of measuring intersurface pressure in the absence of free pericardial effusion (1,11). A continuing concern is that such a device necessarily causes an alteration in the original geometry of the two apposing surfaces, so the pressure measured may be artifactually elevated (10). At least for relatively thin balloon devices, the indirect validation by Smiseth et al. (11) may have answered this criticism. Constraint measurement with an open-ended catheter was accurate in their study only in the presence of 30 ml or greater pericardial effusion.

An artifactually elevated pericardial pressure measurement presumably would have no relation to other physiologic variables. The nearly exact phasic equality of pericardial and right atrial pressure waveforms observed in the current study suggested measurement of true constraint (Fig. 3). Similar findings occur in cardiac tamponade where extracardiac pressure can be measured accurately with an open-ended catheter (24). While such tracking of pericardial and right atrial pressures could reflect local tamponade by the balloon pushing on myocardium, such an effect seems unlikely with the thin balloons used. Furthermore, there was no significant difference in mean pericardial pressure measured using open-ended and balloon catheters in this study

(6 ± 3 versus 7 ± 2 mm Hg), supporting the constraint measurements and suggesting that the physiologic effusions present were sufficient to make the open-ended catheter measurements reasonably accurate.

Effects of opening the pericardium. In both patient groups we found a significant increase in right ventricular stroke work index immediately after pericardiotomy but no significant change in intracavitary right atrial pressure, pulmonary vascular resistance (in Group I) or heart rate. Since reflex changes in contractility are often accompanied by alterations in heart rate, it seems unlikely that this change in right ventricular systolic performance was mediated simply by cardiac stimulation and increased contractility. Because pulmonary vascular resistance did not change significantly in Group I with pericardiotomy, an increase in right ventricular preload may have accounted for the increased performance. Because intracavitary right atrial pressure did not increase significantly, or even decreased, the implied increase in transmural right atrial pressure suggests a significant decrease in extramural pressure with pericardiotomy, providing further support for our direct measurements of pericardial constraint. With pericardiotomy, left ventricular stroke work index showed a borderline significant increase in Group I but not in the more heterogeneous Group II. For large estimated increases in transmyocardial diastolic pressure, however, the increases in ventricular performance after pericardiotomy were relatively small (Fig. 1). Several investigators (25,26) suggested that the Starling reserve above the normal range of operation is limited and, if the stroke work-ventricular diastolic volume relation is truly linear (27), this suggests that the steeply ascending portions of the transmural diastolic pressure-volume curves were reached for both the right and the left ventricle (9).

Global versus local pericardial pressure. Assuming that the pericardium normally matches the shape of the enclosed cardiac chambers, during mid-diastole when both atria and ventricles are filling simultaneously, the pressure of pericardial constraint may be relatively uniform around the heart except for hydrostatic variation with height (8,10). It may not always be uniform, however (28), particularly during interventions causing dramatic change in cardiac shape (29). In the current study balloon pericardial pressure was measured at three separate sites in 11 patients, and the results in diastole were not significantly different. A notable exception was one Group II patient (with mitral stenosis and regurgitation) whose pericardial pressure was 12 mm Hg over the left ventricle, but only 3 to 4 mm Hg over the right heart chambers. In this patient a recent exacerbation of underlying heart disease may have caused a significant change in cardiac shape without sufficient time for pericardial adaptation.

During systole, however, measurements of pericardial surface pressure over the ventricles may be quite nonuniform, reflecting apical impact and other dynamic effects during rapid change in ventricular shape. Although early systolic peaks in pericardial pressure were not prominent in this clinical study, they were sometimes measured over the left ventricle, but not over the right heart chambers. These systolic components were excluded in the average diastolic pericardial pressures given.

Methodologic considerations. Virtually all patients in our study group received significant amounts of intravenous fluid, so an abnormally elevated pericardial constraint pressure could be questioned. However, most patients were also receiving vasodilator medications, which would counteract the effects of volume loading. For instance, the right atrial pressure of 8 ± 2 mm Hg in Group I is close to the normal range for our catheterization laboratory. It is unlikely, however, that intravenous fluids or vasodilators had any direct effect on pericardial capacity.

Median sternotomy itself conceivably may alter pericardial constraint by mediastinal traction. However, in eight patients in Group I and seven in Group II, there was no significant change in right atrial pressure after opening the chest, suggesting no major effect on pericardial constraint. Use of a purse-string suture to secure the 3 mm pericardial opening may have artifactually elevated pericardial pressure. However, even if a small amount of the parietal layer had been tightened locally, the balloon was positioned well away from the insertion site, so an artifactual effect should have been negligible.

Although the frequency response of the balloon catheter was excellent (see Methods), pressure measurement with an additional 72 inch (183 cm) connector line in the operating room would limit this response. Although fine ringing oscillations sometimes were seen (Fig. 3A), the balloon pericardial pressure measurement generally appeared to have adequate frequency response especially as demonstrated by close phasic correlation with the right atrial pressure waveform.

The pericardium appeared grossly normal in all the patients studied and the histologic features appeared normal except for minor changes attributed to surgical trauma. Apparently, the pericardial inflammation that may accompany transmural infarction (five patients in Group I) (30) or rheumatic fever (four patients with rheumatic heart disease in Group II) (31) does not necessarily lead to obvious chronic pericardial abnormality.

The corrections used to calculate left ventricular stroke work index in the presence of valvular lesions were very crude approximations. However, we found no significant change in this variable after pericardiotomy in Group II; therefore, errors from these approximations would not change the hemodynamic conclusions of this study, which depend more on the right than on the left ventricular stroke work calculation.

In three patients in Group I pericardial pressure was 1 to 2 mm Hg greater than right atrial pressure (Fig. 2). Operation with negative transmural diastolic pressure is unlikely except at very reduced levels of ventricular filling (32); this suggests that our pericardial pressure measurement was accurate only within ± 1 mm Hg, contributing to the scatter in the correlation plots. The relatively weak, nonidentity correlation of pericardial and right atrial pressure when Group I was analyzed separately presumably reflected the effect of this scatter within a relatively small total range of variation.

Previous studies. The concept of pericardial constraint has been reviewed elsewhere (15). In the absence of an abnormal effusion, pericardial pressure measurements in human beings have been relatively limited. St. John Sutton and Gibson (33) found a generally low pericardial pressure after cardiac surgery, with the exception of complicating tamponade. However, the solid state transducer catheter they used measures fluid but not necessarily surface pressure (11), and, in the context of postoperative bleeding and clot formation, such a measurement method may not reflect true constraint. More recently, Tyberg et al. (34) found a near identity relation between right atrial and balloon pericardial pressures in nine patients undergoing cardiac surgery. Superior pericardial pressure measurement accuracy, the use of multiple filling conditions in each patient to generate individual curves and a less heterogenous group of patients may have explained the closer correlation obtained in their study.

In contrast to our results, Mangano (35) found no significant change in right and left ventricular stroke work indexes related to right atrial and pulmonary wedge pressures after pericardiotomy. Although differences in anesthesia and patient selection may have contributed to the differences in results, Mangano performed his measurements several minutes after pericardiotomy, whereas our determinations were made immediately after pericardiotomy. A new steady state after pericardiotomy conceivably may include a counter-regulatory decrease in contractility to maintain a relatively fixed cardiac output, potentially obscuring effects of increased preload. Notably, results of pericardiotomy similar to ours were recently reported (36). Mangano et al. (37) also found no change in the relation between radionuclide left ventricular end-diastolic volume and pulmonary wedge pressure after pericardiotomy. However, in this latter protocol, measurements were taken with the pericardium open but the sternum closed and there may have been residual constraint by mediastinal and pulmonary structures.

Implications regarding ventricular diastolic mechanics. The contention that the right ventricle may fill normally with a near-zero transmyocardial diastolic pressure across its free wall may seem counterintuitive. For instance, phasic equalization of intrapericardial and right atrial pressure is commonly found in cardiac tamponade (24), in which the right ventricle is markedly underfilled and often shows diastolic collapse (38). However, during the initial phase of pericardial drainage, intrapericardial pressure continues to equal right atrial pressure and cardiac performance may be normal by the time intrapericardial pressure begins to fall below right atrial pressure (24). Thus, normal as well as reduced right ventricular volumes apparently may exist with near-zero transmural diastolic pressure across the free wall. The ventricular volume that exists at zero transmural diastolic pressure has been termed the equilibrium volume (39). It has been suggested that the end-systolic volume is generally less than the equilibrium volume and that diastolic filling is partly due to elastic recoil (40). Thus, the normally constrained right ventricular free wall may operate near its equilibrium configuration and diastolic filling may reflect elastic recoil as well as venous return which distends the composite myocardial-pericardial free wall, but with the pericardium carrying most of the total transmural diastolic load.

Right atrium and ventricle. Because the right ventricular free wall and septum have different geometric features and are exposed to different transmural diastolic pressures, the concept of a transmural diastolic pressure-volume relation may be an oversimplification for the right ventricle (9). For instance, the ability of the right ventricle to accept normal to elevated diastolic volumes while maintaining a near-zero transmural pressure across the free wall may be caused by high myocardial compliance of the free wall or variation in filling due to septal shift without much change in free wall geometry, or both (9,41). For a sufficient deformation, however, and depending on the compliance characteristics of the free wall, a significant positive transmural pressure would be expected. For example, with the pericardium open, whereas pericardial pressure was rigorously zero, intracavitary right atrial pressure was 7 ± 2 mm Hg in Group I, implying a substantial transmyocardial gradient. Even with the pericardium intact in Group II, mean right atrial pressure was significantly higher than mean pericardial pressure, suggesting that chronic pericardial enlargement may allow right heart dilation sufficient to reach a sizable transmural diastolic pressure (42). The two patients in Group II whose right atrial pressure far exceeded pericardial pressure (that is, the two outliers in Fig. 2) had mitral valve disease and pulmonary hypertension. Thus, the effect of hypertrophy on right ventricular free wall compliance may potentiate the elevation in transmural diastolic pressure allowed by pericardial enlargement. When the pericardium is reasonably normal, however, pericardial and right atrial pressures are similar over a wide range of pressures (43). Thus, the point of deviation of right atrial from pericardial pressure may not be predicted simply by the pressure level, but is a com-

plex function of pericardial capacity and myocardial compliance.

Left ventricle. A large body of work has attempted to characterize the normal and diseased left ventricle by relating intracavitary diastolic pressure to volume (44). The tacit assumption in this analysis that extramural forces are generally negligible may be incorrect. In fact, well known shifts in the intracavitary diastolic pressure-volume relation induced by preload and afterload interventions may be largely mediated by alterations in unmeasured pericardial constraint (3,45–47). A more accurate description of the diastolic left ventricle should relate transmural pressure to volume (9). Where pericardial constraint approximately equals right ventricular diastolic pressure, the pressures outside the left ventricular free wall and septum are similar, so a relatively global transmural left ventricular diastolic pressure may be estimated simply as the difference between left and right ventricular diastolic pressures (15,43). However, the clinical utility and limitations of such a preload index remain to be determined. An elevated pericardial constraint pressure may play a role in chronic as well as acute heart failure states (15,16,48) and may help explain the beneficial effect of diuresis or venodilation in these settings without further compromising systolic performance (15,34,43). Thus, a greater clinical appreciation of pericardial constraint may provide new insights in hemodynamic interpretation and pathophysiology of cardiac disease states.

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